

XII Polish Workshop on Relativistic Heavy-Ion Collisions

Friday 4 November 2016 - Sunday 6 November 2016

Institute of Physics, Jan Kochanowski University

Book of Abstracts

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Session 6 / 36

Some kind words ;-)

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Workshop opening

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Session 2 / 1

Participant number fluctuations for higher moments of a multiplicity distribution

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The independent participant model is generalized for skewness and kurtosis. The obtained relations allow to calculate the fluctuations of an arbitrarily high order. From the comparison with the SPS and the LHC data it is found that the participants are not nucleons. The contribution of the participant fluctuations increases with the order of fluctuations. The bin width correction procedure used for the analysis of fluctuations at the RHIC and the LHC by STAR and ALICE may not cancel participant fluctuations. Another method to quantify the value of participant number fluctuations experimentally is proposed.

arXiv:1606.05358 (will be updated soon)

Session 3 / 30

Stopped nucleons in configuration space

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TBA

Session 2 / 9

Measurement of azimuthal flow of soft and high-pT charged particles in 5.02 TeV Pb+Pb collisions with the ATLAS detector

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The new experimental data collected by the ATLAS experiment during the 2015 heavy ion LHC run offers new opportunities to study properties of Quark-Gluon Plasma at unprecedented high temperatures and densities. Study of the azimuthal anisotropy of produced particles not only constrains our understanding of initial conditions of nuclear collisions and soft particle collective dynamics but also sheds light on jet quenching phenomena via measurement of flow harmonics at high transverse momenta. A new ATLAS measurement of elliptic flow and higher order Fourier harmonics of charged particles in Pb+Pb collisions at 5.02 TeV in a wide range of transverse momenta, pseudorapidity ($|\eta| < 2.5$) and collision centrality will be presented. These measurements will be based on the Scalar Product, Event Plane and Two-Particle Correlation methods. Obtained results will be compared with experimental results at lower collision energies and discussed in the context of theoretical models.

Session 7 / 2

Saturation scale fluctuations and multi-particle rapidity correlations

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The effect of intrinsic fluctuations of the proton saturation momentum scale on event-by-event rapidity distributions is discussed. Saturation scale fluctuations generate an asymmetry in the single particle rapidity distribution in each event resulting in genuine n -particle correlations having a component linear in the rapidities of the produced particles, $y_1 \cdots y_n$. We introduce a color domain model that naturally explains the centrality dependence of the two-particle rapidity correlations recently measured by ATLAS, while constraining the probability distribution of saturation scale fluctuations in the proton. Predictions for $n = 4, 6$ and 8 particle rapidity correlations find that the four- and eight-particle cumulant change sign at an intermediate multiplicity, a signature which could be tested experimentally.

Session 2 / 8

vBag - vector interaction in an extended bag model.

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For studies of quark matter in astrophysical scenarios the thermodynamic bag model is commonly employed. Although successful, it does not account for dynamical chiral symmetry breaking and repulsions due to the vector interaction which is crucial to explain recent observations of massive, two solar mass neutron stars. We developed the novel vBag quark matter model which takes these effects into account and apply it at finite temperatures and isospin asymmetry. Another particular feature of vBag is the determination of the deconfinement bag constant B_{dc} from a given hadronic equation of state (EoS) in order to ensure that chiral and deconfinement transitions coincide. We

discuss consequences of this novel approach for the phase transition construction and the phase diagram.

Session 2 / 4

Quantum field theoretical approach to the shear and bulk relaxation times

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The shear and the bulk relaxation times are important ingredients of the second order hydrodynamics whose success in heavy ion phenomenology is unquestioned. Unlike viscosities themselves, field theoretical calculations of the relaxation times are hard to come by in literature, especially for the bulk relaxation time. In this work, we report two field-theoretical analyses involving the shear and the bulk relaxation time. First, by carefully examining the analytic structure of the stress-energy tensor response functions, we have been able to derive, for the first time, a Kubo formula involving both the shear and the bulk relaxation times. Second, by evaluating the Kubo formula within the massless scalar theory, we have so far been able to calculate the shear relaxation time in a simple form. We will then show how this calculation can be extended to calculate the bulk relaxation time as well.

Session 6 / 3

Stas: fluctuating between theory and experiment

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This is on Stas Mrowczynski fluctuations between theory and experiment

Session 6 / 18

Van der Waals equation of state: from nuclear matter to lattice QCD

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An extension of the ideal hadron resonance gas (HRG) model is constructed which includes the attractive and repulsive van der Waals (VDW) interactions between baryons. This VDW-HRG model yields the nuclear liquid-gas transition at low temperatures and high baryon densities. The VDW parameters a and b are fixed by the ground state properties of nuclear matter.

The temperature dependence of various thermodynamic observables at zero chemical potential are

calculated within VDW-HRG model. Compared to the ideal HRG, the inclusion of VDW interactions between baryons leads to a qualitatively different behavior of 2nd and higher moments of fluctuations of conserved charges, in particular in the so-called crossover region $T=140-190$ MeV. For many observables this behavior resembles closely the results obtained from lattice QCD simulations.

Session 1 / 19

Studies of final-state interactions via femtoscopy in ALICE

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Femtoscopy is a technique allowing measurements of the space-time characteristics of particle production using correlations arising from the effects of quantum statistics and final state interactions. Typically, it is used for measurements of source sizes for pions, kaons, and protons in order to test the hydrodynamic evolution of the system by looking at the dependence of the HBT radii on multiplicity and pair transverse momentum k_T .

The femtoscopic formalism is however sensitive not only to the properties of the source but also to the interaction kernel for a pair of particles, which is directly related to pair interaction cross-section. We show the first measurements of K_S^0 - K^\pm correlation functions in PbPb collisions. These correlations originate from the final-state interactions which proceed through the $a_0(980)$ resonance. The ALICE data show that the a_0 final state interaction describes the measured correlation well. The radii extracted from K_S^0 - K^- and K_S^0 - K^+ systems are found to be equal within uncertainties. The results are also compared with those from ALICE identical-kaon measurements and the parameters of the a_0 resonance are constrained.

The same approach can be applied to baryons to extract the cross-section of the baryon-(anti)baryon interactions. We will show preliminary results from baryon correlations, including protons and Λ s. The extraction of the cross-sections is complicated by the presence of the so-called "residual correlations" originating from the weak decay products. A fitting method accounting for these residual correlations is employed in the case of p - p , p - \bar{p} and \bar{p} - \bar{p} correlations.

Session 1 / 21

Angular correlations of identified particles in pp collisions

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Angular particle correlations are a powerful tool to study numerous properties of the medium (e.g. collective behaviour, jets, quantum statistics or Coulomb effects, conservation laws, decays of resonances). In this talk, we report measurements of di-hadron correlations with respect to the differences in the azimuth ($\Delta\varphi$) and pseudorapidity ($\Delta\eta$) in pp collisions recorded by the ALICE detector. We focus on revealing details of particle production mechanisms.

Analysis of correlations of identified particles in pp collisions reveal big differences in particle production between baryons and mesons. Such effects have usually been connected to conservation laws in e^+e^- collisions and were thought to be under theoretical control; however, results from

hadron collisions are no longer reproduced by the contemporary models implementing those mechanisms (PYTHIA, PHOJET).

Session 7 / 23

Relaxation rates and phase transitions

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Using a bottom-up gauge gravity constructions, relaxation rates of strongly coupled field theories are computed. A variety of phase structures are considered, from a crossover up to a first order phase transition. It is established that near the transition the applicability of a hydrodynamic description breaks down at lower momenta than in the conformal case. In the case of the first order phase transition, a spinodal region appears at temperatures for which the speed of sound squared is negative. An estimate of the preferential scale attained by the unstable modes is also given. Additionally we observe a novel diffusive regime for sound modes over a range of wavelengths.

Session 5 / 22

Anomalous diffusion in a system with a thin membrane

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We consider subdiffusion in a system which consists of two media separated by a thin membrane. The subdiffusion parameters may be different in each of the medium. Using the new method we derive the probabilities (the Green's functions) describing a particle's random walk in the system. From the obtained Green's functions, we derive the boundary conditions at the thin membrane. One of the boundary conditions contains the Riemann-Liouville fractional time derivative, which shows that the additional memory effect is created in the system. The memory effect can be created both by the membrane and by the discontinuity of the medium at the point at which various media are joined. This effect is also created by the membrane for a normal diffusion case. We also present the generalized method of images which provides the Green's functions for the membrane system. This method, which has a simple physical interpretation, is of a general nature and can be used to find the Green's functions for a system with a thin membrane in which various models of anomalous diffusion can be applied. As an example, we find the Green's functions for the particular case of a slow-subdiffusion process in a system with a thin membrane.

Session 1 / 20

Pion spectra and mean multiplicities in Ar+Sc collisions at SPS energies

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The aim of the NA61/SHINE ion programme is to explore the QCD phase diagram within the range of thermodynamical variables accessible by the SPS. In addition the experiment provides precision hadron production measurements for description of the neutrino beam of the T2K experiment at J-PARC and for simulation of cosmic-ray showers for the Pierre Auger Observatory and KASCADE experiments. The main physics goals of the NA61/SHINE ion programme are the study of the properties of the onset of deconfinement and the search for signatures of the critical point of strongly interacting matter. These goals are pursued by performing an energy (beam momentum 13A-158A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Ca, Xe+La, Pb+Pb) scan. In this talk I will discuss recent analysis results of Ar+Sc interactions at six beam momenta: 13A, 19A, 30A, 40A, 75A, 150A GeV/c. I will present the rapidity and transverse mass spectra of pions obtained with the “h-” analysis method.

The procedure of obtaining the final multiplicities will be presented. The mean number of wounded nucleons $\langle W \rangle$ extracted from Glissando MC model is used to obtain the $\langle \pi^- \rangle / \langle W \rangle$ ratio. The newly obtained data will be compared with different collision systems.

Session 2 / 13

Repulsive interactions and their effects on the thermodynamics

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In this talk we compare two approaches in modeling repulsive interactions among hadrons: the excluded-volume approximation and the S-matrix formalism. The latter provides a consistent treatment of broad resonances based on empirical scattering phase shifts. We shall apply these techniques to study the thermodynamics of the $(\pi N \Delta)$ system, with a particular focus on the fluctuation of Baryon charge in the thermal medium.

We show that the introduction of an excluded volume between pions and nucleons, in addition to the interaction that generates the Δ resonance, distorts the phase shift in the P_{33} channel and hence leads to an inconsistent description of the interaction contribution to the thermodynamics.

Session 1 / 25

Recent results from the NA61/SHINE strong interactions program on fluctuations

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NA61/SHINE at the CERN SPS is a fixed-target experiment pursuing a rich physics program including measurements for heavy ion, neutrino and cosmic ray physics. The main goal of the ion program is to study the properties of the onset of deconfinement and to search for the signatures of the critical point.

In this contribution a brief summary of recent results of the NA61/SHINE experiment on fluctuations will be presented. In particular, preliminary results on higher order fluctuations of negatively charged hadrons and net-charge distribution in p+p interactions will be shown. The data will be compared with model predictions.

Session 8 / 17

Vertex Detector of NA61/SHINE experiment for open charm measurements at CERN SPS energies

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The heavy-ion programme of the NA61/SHINE experiment at CERN SPS is expanding to allow precise measurements of exotic particles with short lifetime. The study of open charm mesons allows for investigation of the properties of the hot and dense matter produced in nuclear-nuclear collisions. Vertex Detector for open charm measurements at the SPS is being constructed by the NA61/SHINE Collaboration to meet the challenges of high spatial resolution of secondary vertices and efficiency of track registration.

A small-acceptance version of the Vertex Detector is being tested this year, later it will be expanded to a large-acceptance version. Simulation studies will be presented. A method of track reconstruction in the inhomogeneous magnetic field for the Vertex Detector was developed and implemented. Numerical calculations show the possibility of high precision measurements of charmed particles in heavy ion collisions.

Session 6 / 33

Conversations with Stas on physics and other stuff

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TBA

Session 1 / 11

In-medium modifications of properties of near-threshold kaons in wide range of phase space with FOPI

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Modifications of basic properties of kaons, like mass and decay constants, in hot and dense nuclear medium, often parameterized by the in-medium potentials, are an intensely studied topic in the last two decades. However, until recently the experimental samples obtained from the heavy-ion collisions at 1-2A GeV, and used to draw conclusions on the scale of these potentials were limited to narrow windows of the momentum space [1-4].

An installation of the new RPC-based ToF detector within the FOPI setup at GSI allowed for a considerable enhancement of the kaon acceptance range. Recent measurement of the directed and elliptic flow of charged kaons [5], has been followed by the investigation of the K^-/K^+ ratio across phase space, and was supplemented by the measurement of the Phi mesons, a relevant source of about 20% of negatively charged kaons. This new information may help to sharpen the deduced values of the potentials of interaction of kaons with the medium.

[1] K.Wisniewski et al., Eur. Phys. J. A 9, 515 (2000).

[2] F.Laue et al., Eur. Phys. J. A 9, 397 (2000).

[3] W.Scheinast et al., Phys. Rev. Lett. 96, 072301 (2006).

[4] P.Gasik et al., Eur. Phys. J. A 52, 177 (2016).

[5] V.Zinyuk et al., Phys. Rev. C 90, 025210 (2014).

Session 7 / 27

Can we describe heavy baryons in terms of a pion mean field?

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Viewing a heavy baryon as a system consisting of the $N_c - 1$ light quarks that induce the pion mean field, and a heavy quark as a static color source under the influence of this mean field, we derive a number of model independent relations and calculate the heavy baryon masses using as an input light baryon properties. The results are in remarkable agreement with the experimental data. In addition, the mass of the Ω_b^{**} baryon is estimated. A possibility of applying the same scheme to the doubly heavy $\{q_1 q_2 QQ\}$ tetraquarks is also discussed.

Session 3 / 12

Decelerating Partons and Accelerating Science with SM

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Long before first relativistic CERN-SPS heavy ion collision experiments we have seen models of what may happen to colliding nuclei, with theorists arguing different extreme scenarios: parton transparency, and parton stopping. Similarly we argued about the related mechanism of entropy formation. Today 30 years have passed and these questions continue to be discussed with the same fervor. What this means is that we lack in understanding of how it happens that we generate a fireball of hot and dense parton matter where many had expected two "cooked" nuclei to emerge. Across

several science frontiers of the SM I see that the process of Bremsstrahlung and radiation reaction that was invoked by SM remains an interesting functional simple idea which may help characterize parton deceleration and fireball formation.

Session 4 / 16

Plasma instabilities from hard expanding loops

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I will present a review of analytic and numerical results on the evolution of plasma instabilities in an ultrarelativistic, anisotropically expanding plasma in hard loop effective theory.

Session 5 / 31

About neutrinos and their oscillations

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TBA

Session 8 / 5

Comparative studies of pion spectra in p+p and Pb+Pb collisions (part II)

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In the previous Workshop in this series I addressed the characteristic structures in the ratio of negative pion spectra in Pb+Pb divided by p+p collisions, published by NA61/SHINE collaboration. This included in particular the enhancement of π^- production at low transverse momenta and/or high rapidities.

In the present talk I will discuss this enhancement as an interesting example of convolution of strong and electromagnetic effects, involving both produced pions and spectator nucleons. The evolution of trajectories of charged pions emitted at freeze-out in the EM field of the spectator system, and the possibility of reinteraction with the nuclear remnant, will be studied by means of a relativistic Monte Carlo model and compared to experimental data. The resulting overall effect breaks isospin symmetry, and appears to be directly connected to the charge dependence of the “sea-gull” effect in peripheral Pb+Pb collisions which can now be re-interpreted as a (mainly) electromagnetic and (partially) isospin effect.

Emphasis in the talk will be put on (1) the possibility of using the observed enhancement of π^- production as another independent source of information on the longitudinal space-time evolution of the system, and (2) the excellent acceptance of the NA61/SHINE detector, allowing for detailed studies of not only electromagnetic but also strong phenomena connected to the presence of spectators in Ar+Sc and Pb+Pb collisions.

Session 8 / 15

Pushing fluid dynamics beyond its limits

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The one-dimensional non-boost-invariant evolution of the quark-gluon plasma is analyzed within various frameworks of dissipative fluid dynamics. Predictions of all studied models are similar in the midrapidity region which stays in agreement with recent comparison of their gradient expansions, see arXiv:1608.07558. On the other hand, they differ significantly in the forward/backward region where, in the case of standard viscous formalisms, the plasma undergo large pressure corrections. Their magnitude strongly depends on the particular choice of the second-order terms included, which suggests that the latter should be included in the most complete way. The undesirable growth of viscous corrections results also in the generation of shock fronts which, when applied in event-by-event simulations may distort final results. Both large corrections and shocks are self-regulated in the anisotropic hydrodynamics approach, which uses reorganized hydrodynamic expansion around anisotropic background.

Reference:

W. Florkowski, R. Ryblewski, M. Strickland, L. Tinti, arXiv:1609.06293

Session 3 / 14

Initial State Fluctuations in Heavy Ion Collisions

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I will review recent developments in the description of fluctuating initial conditions in heavy ion collisions.

In particular I will describe the boost invariant Yang-Mills framework and the IP-Glasma model, which are valid at high collision energies.

I will describe various observables, ranging from multiplicity distributions and event-by-event distributions of anisotropic flow coefficients.

I will then discuss the extension of the model to 3 dimensions using JIMWLK renormalization group equations, which resum logarithmically enhanced quantum fluctuations. Within this framework I will present various rapidity dependent observables. Finally, I will discuss the inclusion of quantum corrections beyond the logarithmically enhanced contribution and how a fully 3+1 dimensional simulation will include plasma instabilities and possible isotropization of the non-equilibrium early-time system.

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Special sessions opening

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Session 8 / 24

Proton femtoscopy in BES

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Through experiments with heavy-ion collisions at high energy we can study the properties of nuclear matter under extreme conditions. The information on the sizes of the particle-emitting sources can be inferred via the method of femtoscopy.

The femtoscopy method uses Quantum Statistics effects and the Final State Interactions to determine the space-time properties of the source. The radii of the sources extracted from two-baryon femtoscopy along with those obtained from two-meson and meson-baryon correlations provide complementary information about the source characteristics.

In this talk, a status report of a STAR analysis of proton and antiproton femtoscopic correlations in Au+Au collisions at centre of mass energy of 39 GeV, 11.5 GeV and 7.7 GeV will be presented.

Session 7 / 28

Towards hydrodynamics as an effective theory

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Model studies of equilibration using the AdS/CFT correspondence have led to a number of insights concerning relativistic hydrodynamics; their validity extends well beyond the specific case of N=4 supersymmetric Yang-Mills theory. I will summarise these and assess their impact from the perspective of the physics of quark-gluon plasma.

Session 8 / 10

Examination of the heavy ion collisions using EPOS model in frame of BES program

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Collisions of heavy-ions are major method used to study properties of matter. Such studies are performed with comparison of experimental data and model simulations.

One of theoretical description is Parton-Based Gribov-Regge theory included in the phenomenological model like EPOS. It was originally created to explain the processes at the highest energies obtained with LHC complex. EPOS gives possibility to study different observables what helps to understand better processes present during not only proton-proton collisions but also during much more complex reactions with heavy-ions. Various collision energy scans are considered as well.

So far the EPOS model has been used to describe higher collision energies obtained with RHIC complexes and LHC data. However, there is another interesting program currently under investigation at RHIC: Beam Energy Scan (BES), conducted at Brookhaven National Laboratory. Main goals of this project are to examine the Phase Diagram, to study the characteristics of the first-order phase transition between Hadron Gas and Quark Gluon Plasma phases of nuclear matter. The search of Critical Point between first-order phase transition and transition of “cross-over” is another interesting topic. RHIC, one of the biggest accelerators in the world, collides beams of Au nuclei at selected energies as: $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, \text{ and } 62.4 \text{ GeV}$. The variety of initial conditions provides covering as widest part of Phase Diagram of nuclear matter as possible.

Simulated with EPOS data will be verified using two-particles femtoscopic correlations, which allow one to measure the size of sources determined by newly created particle. The studies of elliptic flow will be performed as well.

Session 6 / 38

Is the QGP created in heavy ion collisions in local thermal equilibrium?

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Session 4 / 7

New vistas in ultraperipheral and peripheral heavy ion collisions

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We present calculation of cross sections for diphoton production in (semi)exclusive $PbPb$ collisions, relevant for the LHC.

The calculation is based on equivalent photon approximation in the impact parameter space.

The cross sections for elementary $\gamma\gamma \rightarrow \gamma\gamma$ subprocess are calculated including two different mechanisms.

We take into account box diagrams with leptons and quarks in the loops.

In addition, we consider a vector-meson dominance (VDM-Regge) contribution

with virtual intermediate hadronic (vector-like) excitations of the photons.

We get much higher cross sections in $PbPb$ collisions than in earlier calculation from the literature.

This opens a possibility to study the $\gamma\gamma \rightarrow \gamma\gamma$ (quasi)elastic scattering at the LHC.

We present many interesting differential distributions which could be measured by the ALICE, CMS or ATLAS Collaborations at the LHC.

We study whether a separation or identification of different components (boxes, VDM-Regge) is possible. We find that the cross section for elastic $\gamma\gamma$ scattering could be measured in the heavy-ion collisions

for subprocess energies smaller than $W_{\gamma\gamma} \approx 15 - 20$ GeV. A first confrontation of our results with very recent

ATLAS data will be given for light-by-light scattering.

We discuss also the two-gluon exchange contribution (formally three-loops) to elastic photon-photon scattering in the high-energy approximation.

The elastic $\gamma\gamma \rightarrow \gamma\gamma$ amplitude is given in the impact-factor representation for all helicity configurations and finite quark masses.

We discuss the importance of including the charm quark, which contribution, due to interference, can enhance the cross section considerably.

We investigate the contribution to the $\gamma\gamma \rightarrow \gamma\gamma$ amplitude from the soft region, by studying its dependence on nonperturbative gluon mass.

Helicity-flip contributions are shown to be much smaller than helicity-conserving ones. We identify region(s) of phase space where the two-gluon exchange contribution becomes important ingredient compared to box and nonperturbative VDM-Regge mechanisms considered in the literature.

Consequences for the $AA \rightarrow AA\gamma\gamma$ reaction are discussed. Several differential distributions are shown.

A feasibility study to observe the effect of two-gluon exchange is presented.

We perform a similar analysis for the $pp \rightarrow pp\gamma\gamma$ reaction. Only by imposing severe cuts on $M_{\gamma\gamma}$ and a narrow window on photon transverse momenta the two gluon contribution becomes comparable to the box contribution but the corresponding cross section is rather small.

We present first measurable predictions for electromagnetic (two-photon) double scattering production of two positron-electron pairs in ultraperipheral heavy-ion collisions at RHIC and LHC.

Measurable cross sections are obtained with realistic cuts on electron/positron (pseudo)rapidities and transverse momenta for the ALICE and ATLAS or CMS experiments.

The predictions for total and differential cross sections are presented. We show also two-dimensional distributions in rapidities of the opposite-sign (from the same or different subcollisions) and of the same-sign (e^+e^+ or e^-e^-) electrons and in rapidity distance between them.

Expected number of events are presented and discussed.

Our calculations strongly suggest that relevant measurements with the help of ATLAS, CMS and ALICE detectors are possible in a near future.

Finally we present results of calculation for total and differential cross sections for J/ψ photoproduction in ultrarelativistic both ultraperipheral and for the first time for peripheral (semi-central)

lead-lead collisions at the LHC energy $\sqrt{s_{NN}} = 2.76$ TeV.

In the present approach we use a simple model based on vector dominance picture and multiple scattering of the hadronic ($c\bar{c}$) state

in a cold nucleus as an example.

In our analysis we use both the classical mechanics and quantum (Glauber) formulae for calculating $\sigma_{tot}(J/\psi Pb)$ which is a building block of our model.

We compare our UPC results with ALICE and CMS data.

For semi-central collisions ($b < R_A + R_B$)

a modification of the photon flux seems necessary.

We discuss different physics motivated approximations.

We try to estimate the cross sections for different centrality bins and for J/ψ mesons emitted in forward rapidity range ($2.5 < y < 4$) corresponding to recent ALICE experimental results.

Reasonable results are obtained but open questions are discussed.

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The critical behavior of hadronic matter: Comparison of lattice and bootstrap model calculations

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Statistical bootstrap model and the related concept of the limiting temperature begun the discussion about phase transitions in the hadronic matter. This was also the origin of the quark-gluon plasma concept. It is discussed here to which extend lattice studies of QCD critical behavior at non-zero chemical potential are compatible with the statistical bootstrap model calculations.

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Entanglement entropy and fluctuations of parity for neutral kaons

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TBA

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Finite volume corrections and low momentum cuts in the thermodynamics of quantum gases

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The ideal boson gas model is used to test the conjecture, proposed in the literature, that the finite volume corrections can be reproduced, with sufficient accuracy, by using the thermodynamic model with the low particle momenta cut off. We find that this is always possible in principle, but simple, convenient formulae are obtained only when the length of the vessel is no less than a few fermi.

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Semirelativity in Semiconductors

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